Electronic Supplementary Material (ESI) for Energy & Environmental Science.

Supplementary information

Historical and projected improvements in net energy performance of power generation technologies

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1. Additional details on choice of analysed technologies

The analysed power generation technologies have been selected to include a fossil-fuel based technology as a reference point and renewables due to their expected importance for future power systems, while taking into account the availability of appropriate historical data.

Within the group of fossil-fuel based technologies, we focus on *hard coal*, which is by far the most important fuel (37% of world electricity generation in 2016).[1] Hard coal-based power generation has been studied broadly in net energy analysis studies in the past, so sufficient data is available to estimate experience curves (in contrast, historical data on other fossil fuel-based technologies is very limited). Thus, hard coal-based power generation serves well as a reference point for the EROI comparison with new technologies.

Within the group of renewables, we include *solar PV* and *onshore wind* as these technologies grew rapidly over the last decades; solar and wind are also generally expected to contribute the majority of new renewable capacity until 2040.[1,2]

In terms of sub-technologies, for hard coal-based power generation both pulverized coal-fired power plants and fluidized bed combustion plants are included, but not integrated gasification combined cycle plants. The latter differ greatly in operation principle and thus is considered a different branch of technology. For solar PV, we consider multi-crystalline silicon PV systems due to their dominance in utility-scale PV installations. For wind turbines, the analysis is limited to onshore plants and to horizontal-axis turbines with a power rating greater or equal to 100 kW as both offshore plants and micro-wind turbines are a separate branch of technology.

Overall, the three analysed technologies are well-suited to developing the concept of energetic experience curves as they include both the most widely deployed technology as well as two relatively new technologies for which improvements through innovation can be expected.

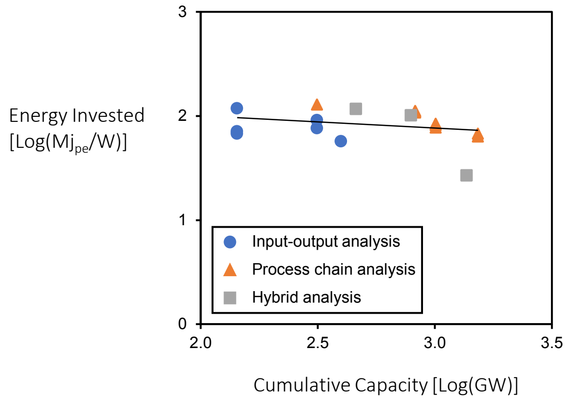
2. Additional details on the data for 'energy invested'

As mentioned in the main text, we use historical data on energy invested from published studies from net energy analysis and life cycle analysis. To start with, a keyword search in scientific databases was conducted. Besides English keywords, we also used German keywords, as an early body of net energy analysis research has been published in German. Databases included

Scopus (Elsevier), Materials Science & Engineering Database, Science Citation Index Expanded (Web of Science), American Chemical Society, nature.com (Nature Publishing Group), American Association for the Advancement of Science, PNAS (National Academy of Sciences). Keywords included “life cycle energy”, “net energy”, “energy analysis”, “net energy analysis”, “EROI”, “embodied energy”, “cumulative energy”, and “payback time”; German keywords included “Energieaufwand”, “kumulierte Energie”, “Nettoenergie”, “energetische Amortisationszeit”, and “energetische Rückzahlzeit”. Also relevant peer-reviewed review papers in the domain of net energy analysis and life cycle analysis have been consulted.[4–7] Third, the results of the literature search have been closely examined and filtered based on a set of criteria to ensure sufficient data quality and comparability among the studies (cf. the criteria discussed in the Methodology part of the main text).

In the relevant literature, different methods have been used, namely process chain analysis (PCA), input-output analysis (I/O), and hybrid analyses (combining PCA and I/O). While PCA is a bottom-up approach that assesses the energy and material balance for each process along the life cycle, I/O is a top-down approach using energy flows between different sectors of the economy which are estimated based on monetary flows and energy intensities. Generally, PCA is considered more accurate,[8] and more recent studies typically use PCA. For each data point used in the present study, Supplementary Tables 1-3 indicate the underlying method. For solar PV, 12 out of 13 data points are based on PCA studies, for wind turbines all 39 data points are based on PCA studies. For hard coal-based power generation, though, 9 data points are based on PCA studies, 6 data points are based on I/O studies, and 3 data points are based on hybrid approaches, resulting in a larger variety of methods. Supplementary Figure 1 illustrates the data points by technology, showing that it is the older studies that rely on I/O. Given the overall small number of available data points (that fulfil the criteria as described in the main text), it is not possible to meaningfully calculate experience rates separately for each method. As a result, the variance among data points for energy invested of hard coal based power generation is high, resulting in the large uncertainty of the respective learning rate as shown in Figure 1 of the main text.

Suppl. Fig. 1: Energy invested for hard-coal based power generation by method of analysis in underlying historical studies



As discussed in the main text, this uncertainty on the experience rates of hard coal-based power generation however does not affect the qualitative results of the paper, such as the ranking and overall trend of the different technologies' EROI. This is due to the fact that hard coal-based power generation has already been so widely deployed that additional installations only have a small effect on its cumulative capacity and thus the projected EROI does not change much over time, irrespective of the experience rates. For the technologies that experience a strong growth in cumulative installed capacity – namely solar PV and wind turbines – the available data is mostly based on PCA, which likely contributes to the smaller variance in data and lower uncertainty on these (highly relevant) experience rates as shown in Figure 1 of the main text.

3. Additional details on historical data for cumulatively installed capacity

Several data sources have been combined because there is no central database that includes cumulatively installed capacities by technology. For hard coal, three sources cover different time spans: 1964–1971,[15] 1972–1999,[16] and 2000–2015.[17] For solar PV, an estimate for 1983[18] and International Energy Agency (IEA) data from 1992 on[19] are used; the curve between 1983 (15 MW) and 1992 (46 MW) is interpolated. For wind, again three sources were required to cover the entire relevant time span: 1980–1994,[20] 1995–1999,[21] and 2000–2016.[22] For each technology, the data in the different studies partly overlap and are largely consistent in the overlapping periods.

4. Additional details on future deployment scenarios

We calculate pathways for future cumulated installed capacity based on IEA projections for operating capacities in 2020, 2025, 2030, 2035, and 2040, using the formula:

$$\text{Cum. installed cap.}_{\text{year i}} = \text{Cum. installed cap.}_{\text{year i - 1}} + \text{Gross cap. additions}_{\text{year i}} \quad [W]$$

With

$$\text{Gross cap. additions.}_{\text{year i}} = \text{Net cap. additions}_{\text{year i}} + \text{Cap. retirements}_{\text{year i}} \quad [W]$$

Net capacity additions ($\text{Operating cap.}_{\text{year i}} - \text{Operating cap.}_{\text{year i - 1}}$) stem from the World Energy Outlook 2016.[23] As the main scenario, we use the IEA's 'New Policies' assumptions (implementation of announced new policies such as the Nationally Determined Contributions under the Paris Agreement); as a 'conservative'/business-as-usual scenario, we use the IEA's 'Current Policies' assumptions (energy policies as of mid-2016 without further changes), and as an ambitious scenario we use the IEA's '450 ppm' assumptions (a pathway consistent with the goal of limiting global warming to 2°C). Since the available IEA projections do not differ between offshore and onshore wind, a growing share of offshore wind capacity as projected by European Wind Energy Association's scenarios[24] is deducted to calculate onshore wind capacity. Capacity retirements build on historical cumulatively installed capacities to derive annual new-build capacities by technology in the past, and they assume retirements after the average technical lifetime by technology as considered by the IEA.[25]

5. Data by technology

Supplementary table 1: Energetic data on hard coal-based power generation.

No.	Reference	Technology status [y]	Energy invested [MJ_{pe}/W]	Capacity [MW]	Capacity factor [-]	Lifetime [y]	Energy delivered [MJ_{el}/W]	EROI [MJ_{el}/MJ_{pe}]
1	Perry et al.[26]	1967	118.6	747	0.65	30	615.0	5.2
2	Perry et al.[26]	1967	71.2	814	0.65	30	615.0	8.6
3	Perry et al.[26]	1967	67.6	904	0.65	30	615.0	9.1
4	Kolb et al.[27]	1974	76.5	1'200	n.a.	25	n.a.	n.a.
5	Inst. of Policy Sc.[28]	1974	128.8	1'000	0.70	30	662.3	5.1
6	Wagner[29]	1974	91.0	1'300	0.80	25	630.0	6.9
7	Tsoulfanidis[30]	1977	57.1	800	0.65	30	615.0	10.8
8	White & Kulcinski[31]	1980	116.8	1'000	0.75	40	946.1	8.1
9	Uchiyama[32]	1993	101.4	1'000	0.75	30	709.6	7.0
10	Spath et al.[33]	1995	110.6	360	0.60	30	567.6	5.1
11	Spath et al.[33]	1995	111.5	425	0.60	30	567.6	5.1
12	Spath et al.[33]	1995	108.3	425	0.60	30	567.6	5.2
13	Spath et al.[33]	2000	84.5	404	0.60	30	567.6	6.7
14	Spath et al.[33]	2000	81.9	404	0.60	30	567.6	6.9
15	Liang et al.[34]	2000	77.6	300	0.57	30	540.0	7.0
16	Wu et al[35]	2007	26.7	1'320	0.57	20	360.0	13.5
17	Liang et al.[34]	2009	67.8	600	0.57	30	540.0	8.0
18	Liang et al.[34]	2009	63.8	1'000	0.57	30	540.0	8.5

Notes: Where needed, data is converted to MJ of primary energy per Watt of installed electrical capacity. Data points no. 1 – 4, 6 – 7 are based on input-output analysis; data points 5, 10–15, 17–18 are based on process chain analysis; data points 8–9, 16 are based on a hybrid approach. For data point no. 4, information on capacity factor is not available. Data point no. 5 is cited from a synopsis in IAEA 1994[36].

Supplementary table 2: Energetic data on solar PV.

No.	Reference	Technology status	Energy invested	Lifetime	Perfor-mance ratio	Energy delivered	EROI
		[y]	[MJ_{pe}/W]	[y]	[-]	[MJ_{el}/W]	[MJ_{el}/MJ_{pe}]
1	Kreith et al.[37]	1986	160.8	30	0.74	78.1	0.49
2	Schaefer & Hagedorn[38]	1989	72.0	30	0.75	78.7	1.09
3	Wetzel et al.[39]	1993	68.4	30	0.75	79.6	1.16
4	Tripanagnostopoulos et al.[40]	1997	36.0	30	0.77	81.4	2.26
5	Ito et al.[41]	1999	26.8	30	0.78	82.5	3.08
6	Koroneos et al.[42]	2000	32.5	30	0.78	82.2	2.53
7	IER[43]	2001	21.6	30	0.82	85.9	3.98
8	Alsema & De Wild-Scholten[44]	2004	34.3	30	0.83	87.2	2.54
9	Raugei et al.[45]	2005	35.3	30	0.85	89.5	2.53
10	Raugei et al.[45]	2007	34.4	30	0.84	88.5	2.57
11	De Wild-Scholten[46]	2011	15.8	30	0.87	92.1	5.83
12	De Wild-Scholten[46]	2011	18.9	30	0.87	92.1	4.88
13	Hou et al.[47]	2013	6.5	30	0.89	93.4	14.45

Notes: Where needed, data is converted to MJ of primary energy per Watt of installed electrical capacity. Data point no. 1 is based on input-output analysis; data points 2–13 are based on process chain analysis. As the empirical evidence of improving or worsening technical lifetime of PV systems is sparse (variations in reported values between 20 and 40 years primarily reflect different planning assumptions)[48], lifetime is assumed constant in line with IEA guidelines[49]. The performance ratio PR is calculated according to median PR values provided by Reich et al.[50] (see methods) with values for technology status years outside the installation years from Reich et al. (2000 – 2009) extrapolated based on a double-logarithmic learning curve for PR. Assumptions for average plane of array irradiance H_{POA} of 1,055 kWh y^{-1} m^{-2} and for the degradation rate $r_{degradation}$ of 0.5% are conservative for Germany according to Fraunhofer ISE.[51] The irradiance intensity under standard test conditions G_{STC} is 1,000 W m^{-2} as defined by IEC 60904-3.

Supplementary table 3: Energetic data on wind turbines.

No.	Reference	Technology status [y]	Energy invested [MJ_{pe}/W]	Capacity [MW]	Capacity factor [-]	Lifetime [y]	Energy delivered [MJ_{el}/W]	EROI [MJ_{el}/MJ_{pe}]
1	Gydesen et al.[52]	1987	5.0	0.150	0.142	20	89.6	18.0
2	Myslik[53]	1987	5.7	0.300	0.142	20	89.6	15.9
3	Hagedorn & Illmberger[54]	1988	7.9	0.225	0.143	20	90.5	11.4
4	Hagedorn & Illmberger[54]	1988	5.4	0.300	0.143	20	90.5	16.7
5	Pernkopf[55]	1988	7.0	0.100	0.143	20	90.5	12.9
6	Pernkopf[55]	1988	7.7	0.165	0.143	20	90.5	11.8
7	Pernkopf[55]	1988	6.1	0.200	0.143	20	90.5	14.9
8	Pernkopf[55]	1988	7.8	0.265	0.143	20	90.5	11.6
9	Pernkopf[55]	1988	9.3	0.450	0.143	20	90.5	9.7
10	Domrös[56]	1989	7.1	0.300	0.145	20	91.4	12.8
11	Lewin[57]	1990	6.6	0.300	0.147	20	92.5	14.0
12	Roth[58]	1991	15.7	0.300	0.149	20	93.7	6.0
13	Stelzer & Wiese[59]	1991	3.2	0.500	0.149	20	93.7	29.6
14	Frischknecht et al.[60]	1993	23.8	0.150	0.154	20	97.1	4.1
15	Wiese & Kaltschmitt[61]	1993	9.7	0.100	0.154	20	97.1	10.0
16	Wiese & Kaltschmitt[61]	1993	8.0	1.000	0.154	20	97.1	12.2
17	Kuemmel & Sorensen[62]	1994	8.6	0.400	0.157	20	98.8	11.5
18	White[63]	1994	2.9	3.488	0.157	20	98.8	34.4
19	Nadal[64]	1995	11.1	0.225	0.162	20	102.4	9.2
20	Vorspools et al.[65]	1996	7.2	0.600	0.167	20	105.2	14.6
21	Vorspools et al.[65]	1996	7.0	0.600	0.167	20	105.2	15.0
22	Gürzenich et al.[66]	1997	9.2	1.500	0.171	20	107.8	11.7
23	Gürzenich et al.[66]	1997	9.0	1.500	0.171	20	107.8	11.9
24	Gürzenich et al.[66]	1997	9.1	1.500	0.171	20	107.8	11.8
25	Pick & Wagner[67]	1997	7.9	0.500	0.171	20	107.8	13.7
26	Pick & Wagner[67]	1997	8.7	0.500	0.171	20	107.8	12.4
27	Pick & Wagner[67]	1997	10.0	0.500	0.171	20	107.8	10.8
28	Pick & Wagner[67]	1997	9.1	1.500	0.171	20	107.8	11.9
29	Schleisner[68]	1997	5.2	0.500	0.171	20	107.8	20.8
30	White[63]	1998	9.7	0.750	0.183	20	115.1	11.9
31	White[63]	1998	11.6	0.600	0.183	20	115.1	9.9
32	Ardente et al.[69]	2004	6.3	0.660	0.232	20	146.4	23.4
33	Tremeac & Meunier[70]	2004	15.6	4.500	0.232	20	146.4	9.4
34	Guezuraga et al.[71]	2006	2.9	2.000	0.224	20	141.6	49.0
35	Guezuraga et al.[71]	2006	7.0	1.800	0.224	20	141.6	20.1
36	Martinez et al.[72]	2006	4.2	2.000	0.224	20	141.6	33.5
37	Al-Behadili & El-Osta[73]	2007	12.0	1.650	0.230	20	145.0	12.1
38	Merugula et al.[74]	2007	6.4	2.000	0.230	20	145.0	22.8
39	Kabir et al.[75]	2009	7.1	0.100	0.215	20	135.6	19.2

Notes: Where needed, data is converted to MJ of primary energy per Watt of installed electrical capacity. All data points are based on process chain analysis. Data points no. 1–12, 14–17, 19 are cited from a synopsis in Lenzen & Munksgaard 2002[5]. As for solar PV, lifetime is assumed constant. Capacity factors are calculated for German conditions (see methods).

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